Kevin Carlberg

Research interests

Reduced-order modeling, High-performance computing, Multiphysics simulations, Machine learning, Uncerrtainty quantification, PDE-constrained optimization, Surrogate modeling, Iterative solvers for sparse linear systems, Computational fluid dynamics, Finite element analysis

Education

2006–2011 **Ph.D., Aeronautics & Astronautics**, *Stanford University*.
Ph.D. Minor: Computational and Mathematical Engineering
Research Adviser: Dr. Charbel Farhat
GPA: 4.15/4.0

2005–2006 **M.S., Aeronautics & Astronautics**, *Stanford University*.
GPA: 4.21/4.0
ranked 1st in class

2001–2005 **B.S., Mechanical Engineering**, *Washington University in St. Louis*.
GPA: 4.0/4.0
summa cum laude
Valedictorian

Doctoral thesis

title *Model Reduction of Nonlinear Mechanical Systems via Optimal Projection and Tensor Approximation*

adviser Dr. Charbel Farhat

description Time-critical applications for dynamical systems—such as control, fast-turnaround design, and uncertainty quantification—often demand the accuracy provided by large-scale computational models, but cannot afford their computational cost. To mitigate this bottleneck, researchers have developed reduced-order modeling techniques that decrease the dimension of the dynamical system while preserving its key features. Such methods are effective when applied to specialized problems (e.g., linear time-invariant systems) However, model reduction for nonlinear systems has been primarily limited to methods based on the proper orthogonal decomposition (POD)—Galerkin approach, which lacks 'discrete optimality' and leads to unstable responses in many cases. To this end, this thesis presents two model-reduction techniques that address the shortcomings of POD–Galerkin. The first method is a 'compact POD' reduced-order basis, which is constructed using a goal-oriented framework and is applicable to parameterized static systems. The second method is a Gauss–Newton with approximated tensors (GNAT) method that is 'discrete optimal' and is applicable to nonlinear dynamical systems.

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President Harry S Truman Fellow, Sandia National Laboratories

Research experience (selected)

Sandia National Laboratories, Quantitative Modeling & Analysis Dept, Livermore, CA.

May 2013–present
Model reduction for quantum-mechanical systems.
- Developing a method to preserve structure for quantum-mechanical systems to enable real-time control in quantum computing.
- *Collaborators*: Mohan Sarovar

December 2011–present
Decrease the temporal complexity for nonlinear reduced-order models.
- Developed a technique that exploits time-domain data to accurately forecast the solution at future time steps. The Newton solver employs this forecast as an initial guess.
- Decreased computational times by a factor of two with no loss in accuracy for reduced-order models of a finite-element truss structure model.
- Associated publication: [1]
- *Collaborators*: Jaideep Ray, Bart van Bloemen Waanders

December 2011–present
Preserve classical Lagrangian and Hamiltonian structure in nonlinear model reduction.
- Developed a model-reduction method that preserves Lagrangian structure—which associates with critical properties such as energy conservation and symplectic time-evolution maps—and leads to efficiency in the presence of high-order nonlinearities.
- Demonstrated greatly improved accuracy and stability over existing model-reduction methods on a geometrically nonlinear structural-dynamics problem.
- Associated publication: [6]
- *Collaborators*: Ray Tuminaro, Paul Boggs

March 2012–present
A Trilinos-based module for nonlinear model reduction.
- Developed a model-reduction interface to equip Trilinos-based simulation codes for nonlinear model reduction.
- Significantly decreased the barrier to entry for implementing model-reduction methods in different Trilinos-based codes.
- *Collaborators*: Julien Cortial (project lead), Andy Salinger

November 2012–present
Uncertainty quantification for reduced-order models.
- Developed a statistics-based approach to quantify the uncertainty introduced by the use of a reduced-order model *in lieu* of the full-order computational model.
- Method exploits physics-based error indicators, e.g., error bounds and dual-norm residuals.
- Successfully integrated reduced-order models in an uncertainty-quantification framework.
- *Collaborators*: Martin Drohmann (project lead), Khachik Sargsyan

Stanford University, Farhat Research Group, Stanford, CA.

2008–2011 **Fast-turnaround design of Toyota Formula One cars using reduced-order models**.

- Developed a model reduction technique that uses data reconstruction to accelerate large-scale nonlinear simulations. Achieved speedups over 100x with errors less than 5% on structure, fluid, electronic, and neuron models;
- Devised a model reduction method that decreases the cost of nonlinear simulations via a quasi-Newton technique. Obtained speedups around 7x with errors below 5% on car aerodynamics problems;
- Implemented these methods in AERO-F: the group's massively parallel, compressible, Navier-Stokes finite-volume solver.
- Associated publications: [2, 4, 7]
- *Collaborators*: Charbel Farhat, Charbel Bou-Mosleh, David Amsallem, Julien Cortial

2007–2009 **Efficient PDE-constrained optimization**.

- Developed an iterative solver that uses model reduction concepts to accelerate solving sequences of sparse linear systems that arise in PDE-constrained optimization. Achieved speedups over 7x on V-22 Osprey wing panel model.
- Implemented this solver in the group's domain decomposition-based structural mechanics finite element code.
- Devised a low-cost, goal-oriented model reduction method for steady-state systems. Improved both efficiency and accuracy compared with standard model reduction methods on a large-scale aeroelastic research wing model.
- Associated publications: [3, 9, 10]
- *Collaborators*: Charbel Farhat

Engineering Software Research and Development, Inc., St. Louis, Missouri

2003–2005 **Contact capability in finite-element software**.

- Assisted implementing contact capability into StressCheck, a commercial finite element analysis software package.
- *Collaborators* Barna Szabo, Ricardo Actis

Buerge Engineering Corporation, St. Louis, Missouri

2003–2005 **Active flow control experimentation**.

- Devised and conducted wind-tunnel experiments to analyze the effect of surface blowing as a form of active flow control on the aerodynamic performance of a cylinder. Obtained lift-to-drag ratios exceeding 1.2.
- Designed and built an economical, induced-flow, open test-section wind tunnel.

Teaching and research advising

Instructor and Curriculum Developer

Summer 2009–10 **Introduction to Engineering Optimization**, *Army High-Performance Computing Research Center Summer Institute*, Stanford, CA.

Teaching Assistant

Spring 2010 **Large-Scale Numerical Optimization (CME 338)**, *Stanford University*, Prof Michael Saunders.

Fall 2004, Spring 2005 **Mechanics of Deformable Bodies (ME 241)**, *Washington University in St. Louis*, Prof Barna Szabo.

Research Advising

October 2012–present **Martin Drohmann**, *Postdoctoral researcher*, Sandia National Laboratories.
Project: Uncertainty quantification for reduced-order models

February 2012–present **Julien Cortial**, *Postdoctoral researcher*, Sandia National Laboratories.
Project: A Trilinos-based module for nonlinear model reduction

Fall 2010 **Wade Spurlock**, *M.S. Aeronautics & Astronautics*, Stanford University.
Project: Visualizing nonlinear model reduction methods for Formula One car design

Summer 2010 **Matthew Zahr**, *B.S. Civil Engineering*, University of California, Berkeley.
Project: Comparing model reduction methods on linear and nonlinear electrical, mechanical, & biological systems. Won "best project" at AHPCRC 2010 Summer Institute.

Fall 2009 **Paul Covington**, *M.S. Computational & Mathematical Engineering*, Stanford University.
Project: Implementing shape sensitivity analysis in a massively parallel fluid code.

Honors and awards

2011–2014 **President Harry S. Truman Fellowship**, Sandia National Laboratories.

2008–2010 **National Science Foundation Graduate Research Fellowship**, Stanford University.

2008 **CEA-EDF-INRIA Numerical Analysis Summer School Scholarship**, Paris, France.

2007 **Nicholas J. Hoff Award**, *ranked 1st in graduating M.S. class of Aeronautics & Astronautics*, Stanford University.

2006 **Ranked 1 of 16 in Aeronautics & Astronautics Ph.D. qualifying exams**, Stanford University.

2005–2008 **National Defense Science and Engineering Graduate Fellowship**, Stanford University.

2005 **Gustav Mesmer Prize**, *ranked 1st in graduationg B.S. class of Mechanical Engineering*, Washington University in St. Louis.

2001–2005 **Calvin L. Woodward Fellowship**, Washington University in St. Louis.

2001–2005 **Danforth Scholarship**, Washington University in St. Louis.

Academic service

2009–present **Journal referee**.

- *Computer Methods in Applied Mechanics and Engineering*
- *Computers and Fluids*
- *International Journal for Numerical Methods in Engineering*
- *International Journal for Numerical Methods in Fluids*
- *Journal of Computational and Applied Mechanics*
- *SIAM Journal on Optimization*
- *SIAM Journal on Scientific Computing*

2013 **Scientific committee member**, *2nd ECCOMAS Young Investigators Conference*, Bordeaux, France.

2011 **External examiner for postgraduate courses**, *University of Pretoria*, South Africa.

2009–2010 **Student search-committee member**, *Faculty Search Committee*, Stanford University Aeronautics & Astronautics.

2009–2011 **Seminar lead**, *Farhat Research Group Seminar Series*, Stanford University.

Journal

Recent preprints

[1] K. Carlberg, J. Ray, and B. van Bloemen Waanders. Decreasing the temporal complexity for nonlinear, implicit reduced-order models by forecasting. *arXiv e-print*, (1209.5455), 2012.

Published

[2] K. Carlberg, C. Farhat, J. Cortial, and D. Amsallem. The GNAT method for nonlinear model reduction: effective implementation and application to computational fluid dynamics and turbulent flows. *Journal of Computational Physics*, 242:623–647, 2013.

[3] K. Carlberg and C. Farhat. A low-cost, goal-oriented 'compact proper orthogonal decomposition' basis for model reduction of static systems. *International Journal for Numerical Methods in Engineering*, 86(3):381–402, April 2011.

[4] K. Carlberg, C. Farhat, and C. Bou-Mosleh. Efficient non-linear model reduction via a least-squares Petrov–Galerkin projection and compressive tensor approximations. *International Journal for Numerical Methods in Engineering*, 86(2):155–181, April 2011.

[5] D. Amsallem, J. Cortial, K. Carlberg, and C. Farhat. A method for interpolating on manifolds structural dynamics reduced-order models. *International Journal for Numerical Methods in Engineering*, 80(9):1241–1258, 2009.

Conference papers (refereed)

[6] K. Carlberg, R. Tuminaro, and P. Boggs. Efficient structure-preserving model reduction for nonlinear mechanical systems with application to structural dynamics. In *AIAA Paper 2012-1969, 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii*, April 23–26 2012.

[7] K. Carlberg, J. Cortial, D. Amsallem, M. Zahr, and C. Farhat. The GNAT nonlinear model reduction method and its application to fluid dynamics problems. *AIAA Paper 2011-3112, 6th AIAA Theoretical Fluid Mechanics Conference, Honolulu, HI*, June 27–30, 2011.

[8] R. Stephan and K. Carlberg. Gappy data reconstruction and applications in archaeology. In *Proceedings of the XXXVIII Annual Conference on Computer Applications and Quantitative Methods in Archaeology*, April 6–9, 2010.

[9] K. Carlberg and C. Farhat. An adaptive POD-Krylov reduced-order model for structural optimization. *8th World Congress on Structural and Multidisciplinary Optimization, Lisbon, Portugal*, June 1–5 2009.

[10] K. Carlberg and C. Farhat. A compact proper orthogonal decomposition basis for optimization-oriented reduced-order models. *AIAA Paper 2008-5964, 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Victoria, Canada*, September 10–12, 2008.

Talks

Invited

- K. Carlberg, "The GNAT method for nonlinear model reduction: discrete optimality, practical implementation, & application to CFD," Virginia Tech Math Colloquium, Virginia Tech, Blacksburg, VA, April 19, 2013.
- K. Carlberg, "Discrete-optimal nonlinear model reduction by the GNAT method," ACDL Seminar, MIT, Boston, MA, April 17, 2013.
- K. Carlberg, "The GNAT method for nonlinear model reduction: overview and perspectives on UQ application," Uncertainty Quantification Laboratory Seminar, Stanford University, Stanford, CA, May 3, 2012.
- K. Carlberg and C. Farhat, "The Gauss–Newton with approximated tensors (GNAT) method for nonlinear model reduction," SUPRI-B Group Seminar, Stanford University, Stanford, CA, June 1, 2011.
- K. Carlberg and C. Farhat, "Model reduction-based iterative methods for real-time simulation and repeated analyses of mathematical models," Linear Algebra and Optimization Seminar, Stanford University, Stanford, CA, October 28, 2010.
- K. Carlberg and C. Farhat, "An adaptive POD-Krylov reduced-order modeling framework for repeated analyses problems," 2009 Joint ASCE-ASME-SES Conference on Mechanics and Materials, Blacksburg, VA, June 27, 2009.

Conference

- K. Carlberg, C. Farhat, J. Cortial, and D. Amsallem, "The GNAT nonlinear model-reduction method with application to large-scale turbulent flows," Fourth International Workshop on Model Reduction in Reacting Flows (IWMRRF), San Francisco, CA, June 19–21, 2013.
- K. Carlberg, R. Tuminaro, and P. Boggs, "Preserving Lagrangian Structure in Nonlinear Model Reduction," 2013 SIAM Conf on Comp Sci & Eng, Boston, MA, February 25–March 1, 2013.
- K. Carlberg, J. Ray, and B. van Bloemen Waanders, "A forecasting method for decreasing the temporal complexity in implicit, nonlinear model reduction," MoRePaS II, Gunzburg, Germany, July 8–13, 2012.
- K. Carlberg, C. Farhat, J. Cortial, and D. Amsallem, "The GNAT method for nonlinear model reduction: recent developments and application to large-scale models," 10th World Congress on Computational Mechanics, Sao Paulo, Brazil, July 8–13, 2012.
- K. Carlberg, J. Ray, and B. van Bloemen Waanders, "Decreasing the temporal complexity in nonlinear model reduction," 2012 Siam Conf on Uncertainty Quantification, Raleigh, NC, April 2–5, 2012.
- K. Carlberg, D. Amsallem, C. Bou-Mosleh, and C. Farhat, "Efficient Model Reduction of Large-Scale Nonlinear Systems in Fluid Dynamics," 2011 SIAM Conf on Comp Sci & Eng, Reno, NV, February 28–March 4, 2011.
- K. Carlberg and C. Farhat, "Nonlinear model reduction using Petrov-Galerkin projection and data reconstruction," 2010 SIAM Annual Meeting, Pittsburgh, PA, July 13, 2010.

- K. Carlberg and C. Farhat, "A proper orthogonal decomposition-based augmented conjugate gradient algorithm for nearby problems," 2009 SIAM Annual Meeting, Denver, CO, July 7, 2009.
- K. Carlberg and C. Farhat, "A POD-based iterative solver for fast structural optimization," Seoul National University-Stanford University Student Joint Workshop, Stanford University, June 18, 2009.

Other skills

- C++, Matlab programming
- High-performance computing
- Unix
- LaTeX

Other interests

- Marathons
- Backpacking
- Downhill skiing
- Open-water swimming
- Triathlons
- Kayaking
- Cycling

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